

## The History of Orbiter Corrosion Control (1981 – 2011)

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### Introduction

The Space Shuttle Orbiter is a truly remarkable vehicle (Figure 1). As the first orbital spacecraft design for reuse it has served America's space program tremendously for three decades. The Orbiter was designed for a life of 10 years or 100 missions. Although none of the vehicles have flown more than 39 missions the Orbiter has performed spectacularly for three times its designed life.



Figure 1. The Space Shuttle Atlantis on orbit.

Although a complex vehicle, its basic construction is not much different than a normal aircraft (Figure 2). What make the Orbiter unique are its thermal protection and other systems which were designed to operate over a wide range of operating temperatures, pressures and stresses. The Orbiter utilizes aggressive fluid systems which can create challenges both in operation and during ground operations. Additionally the Orbiter spent a good portion of its life in one of the world's most aggressive sea coast environments. Another challenge was the fact that the Orbiter's structure and systems were not necessarily designed for inspectability.

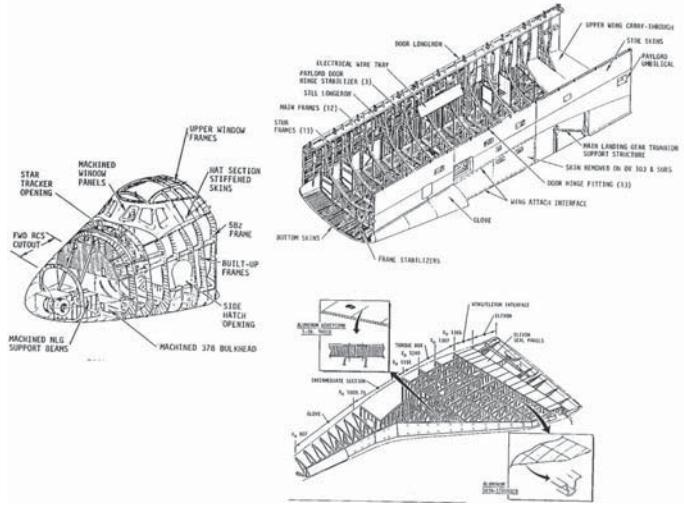


Figure 2. Select cross sections highlighting the basic structural design of the Orbiter

In 1993 after approximately 10 years of operation a Corrosion Control Review Board (CCRB) was formed by Orbiter management. The goals of the CCRB included an assessment of the extent and cause of corrosion, the provision of both long term and short term corrective actions, the generation and maintenance of a historical corrosion database, the development and implementation of methods for the detection of corrosion and the development and implementation of corrosion training and certification programs.

The CCRB drew its core membership from the Materials and Processes discipline and Safety and Mission Assurance (S&MA) Engineers from both NASA and the prime contractors. The CCRB also received regular support from structures engineering and from specialist from various NASA organizations in fields such as chemistry, materials science and nondestructive evaluation.

### **Design Considerations<sup>(1)</sup>**

The majority of the Orbiter's life was spent in processing facilities which were temperature and humidity controlled. However, when each vehicle moved to the launch pads it was subjected to an almost constant salt spray from the ocean. High humidity also allowed for the formation of condensation on all surfaces open to the atmosphere. This condensation would evaporate in the vacuum of space, but as was later discovered could leave behind corrosive residues. After landing the Orbiter was deserviced and exposed to exterior environments. The duration of exposure would be dependent on the landing site. If the Orbiter landed away from the Kennedy Space Center, a ferry flight would be required; exposing the vehicle to additional uncontrolled environments. All these factors were taken into consideration when the overall corrosion protection scheme was developed.

A detailed material control and corrosion protection plan was developed by the design contractor (Rockwell). This plan required an ‘A’ rating for both corrosion and stress corrosion for all materials. Metallic materials were required to meet MSFC-SPEC-250<sup>(2)</sup>, class II requirements. If a material could not meet these requirements they were evaluated and approved based on their use, location or protection scheme. The guideline document for stress corrosion cracking was MSFC-SPEC-522<sup>(3)</sup>.

Galvanically dissimilar materials were restricted by requiring that they not be in contact unless suitably protected against electrolytic corrosion. Faying surfaces of dissimilar metals were required to be sealed against water intrusion or they were separated with a layer of corrosion-inhibiting epoxy or room-temperature vulcanized (RTV) silicone rubber. All fasteners were we installed with a chromated epoxy primer.

Some special design considerations were implemented such as a dry nitrogen gas purge system for the interior spaces and drain holes to prevent water accumulation.

### **Unanticipated Events**

As would be expected in any long term operational program unanticipated events occurred which were of particular interest to the CCRB. The normal anticipated pad stay was approximately 31 days. However, flight delays often extended these stays in the harsh costal atmosphere. For example Columbia spent 166 days at the pad prior to its tenth flight. This caused concerns for the protection of exterior or un-purged areas such as the rubber speed brake, wing leading edge spar and external tank doors.

Other anticipated events included frequent use of the pad Firex system which is activated when potential fire hazards are present. On one occasion, the Firex system was inadvertently activated in the Orbiter processing facility. A greater than expected amount of water intrusion was found during pad stays, ferry flight or mate/demate operations at the landing facilities. Finally, there were several cases of unanticipated spillage of hypergolic fuels and oxidizers.

### **Inspection Methods**

The majority of corrosion inspections on the Orbiter were performed visually. Most of the inspection intervals were documented in the airframe inspection section of what was called the Operations Maintenance Requirements and Specification Document (OMRSD). Visual inspections could be done using aids such as flashlights, 5x-10x magnification, mirrors and borescopes. In some case removal of components and/or surface cleaning was required. The OMSRD gave details for visual inspection requirements for not less than 18 inches away.

### **Life Extension**

The Orbiter project went through two major efforts to evaluated life extension. The first effort extended the Orbiter life to 20 years and the second to 30 years and beyond.

During the second effort a program titled Aging Vehicle Assessment (AVA) was instituted. A separate corrosion control assessment was part of this and was partnered and directed by CCRB members from The United Space Alliance and Boeing. The AVA program provided a complete

review of the Orbiter's corrosion control program and provided the CCRB with an extensive list of products for the remainder of the program<sup>(4)</sup>.

The major products of the AVA program included a baselining effort which established a starting point from which to compare from. Next prioritization, which included identification of the top recurring corrosion problem areas were evaluated. Then prevention and detection method were studied. Then reaction and mitigation practices were evaluated. Trending was reevaluated and upgrades to the database were made.

### Select CCRB Accomplishments

One of the cornerstone objectives of the CCRB was to suggest and implement process improvements, tools and other enhancements. These efforts directly coincided with the aforementioned life extension efforts. One of the first tools developed early on was corrosion database. This database was created in the early 1990's and represented a historical review of all Orbiter problem reports and corrective actions. The database was based on a keyword search and each entry was screened by CCRB members to assure adequacy.

Other CCRB activities included the evaluation of inspection techniques and requirements. For general inspection, the CCRB decided that visual inspection was adequate. To assure consistency the CCRB help to develop specialized corrosion inspection training. For critical structural inspections only inspectors who had received this specialized training were allowed to perform the inspections.

In some cases more advanced nondestructive evaluation techniques were used. These included eddy current, ultrasonic, dye penetrant, x-ray, infrared thermography and terahertz. Examples include the use of eddy current for evaluation of corroded fastener collars, ultrasonic for evaluation of internal corrosion of cold plates, infrared thermography for evaluation corrosion under paint and terahertz for the evaluation of corrosion under thermal protection system tiles.

To further enhance operations the CCRB developed standard corrosion repair procedures.<sup>(5)</sup> These procedures were consistent standard commercial and military aviation practices. The procedures included specific instructions on the evaluation, removal (chemical vs. physical) and repair of corrosion damage.

### Corrosion Preventative Compounds (CPCs)<sup>(6)</sup>

The use of CPCs is common in military and commercial aviation. A CPC is common term given to coatings such as oils or greases that possess a corrosion inhibiting effect. To use a CPC on the Orbiter would require that the material could be applied to reach potential corrosion sites, be stable in a space environment and not to produce contamination.

After a review of commercially available products, ten were selected for testing. Testing performed included salt spray (after vacuum exposure), seaside exposure, flammability, hypergolic compatibility, liquid oxygen compatibility and outgassing.

After testing three components were selected for application to the Orbiter. A waxy hydrocarbon material which could be applied via spray on select interior services such as the rudder speed brake, vertical tail, body flap and elevons. The same material was applied via brush to the vent doors, external tank door cavities (hydrogen side only), carrier panels and wing leading edge faying surfaces. A second material, a calcium grease, was selected and was applied to both the rudder speed brake and body flap actuators as well and the elevon cover primary seal tubes. Finally, a fluid film was qualified for various ground support equipment applications.

As part of the AVA program a test program was performed to establish the mission life cycle of approved CPCs.<sup>(7)</sup> All CPCs used on the Orbiter were tested in conditions to simulate multiple mission cycles. A mission cycle included four months in the Orbiter Processing Facility (OPF), three weeks in the Vehicle Assembly Building (VAB), one month at the pad and two weeks in low earth orbit. For the purpose of the study the OPF and VAB stays were considered to have no life limiting effects. Test panels were subjected to high and low temperatures to simulate ascent and decent conditions. It was decided to use four weeks at the beach facility or one week in salt fog plus two weeks in a vacuum chamber to simulate one mission cycle. Coupons were tested at two NASA centers with beach site and a  $10^{-2}$  Torr vacuum exposure at the Kennedy Space Center (KSC) and salt fog and a  $10^{-6}$  Torr vacuum exposure at Marshall Space Flight Center (MSFC). Four mission cycles were run at KSC and five at MSFC.

To evaluate the performance of the CPCs electrochemical Impedance Spectroscopy (EIS) was used. EIS was selected because it measures both the deterioration of the organic coating caused by exposure to an electrolyte and the subsequent increase in corrosion rate caused by this deterioration. EIS detects changes in the coating in advance of any visible evidence. This study concluded that the waxy hydrocarbon material performed the best and was still effective in protecting against corrosion after four mission cycles. The calcium grease also performed well and was effective for two mission cycles.

### Aging Primer

One of the issues that plagued the Orbiter team was the inability to replace coatings. Depainting was inherently difficult and expensive. Depainting creates contamination and degenerates airborne debris. Access was difficult since a large amount of hardware disassembly was required and special platforms would need to be constructed. Additionally, the cost and schedule impacts were great. Over the life of the program a few select depainting operations were performed on areas such as the rubber speed brake and wing lead edge spars.

Since replacement was problematic an aging study of the Orbiter's Super Koropon primer was performed<sup>(8)</sup>. For this study an aluminum access panel from the first Orbiter built, the Enterprise, was obtained. In a salt fog test of this primer corrosion was observed after 500 hours of testing. A coupon with freshly applied primer passed the 1500 hour test with no corrosion. To further investigate samples from both the Enterprise Koropon and the freshly applied Koropon were analyzed via scanning electron microscopy (SEM).

A comparison SEM image is shown in Figure 3. Even with the difference in magnification the differences between the images is apparent. The Enterprise sample is very rough and flaky while

the control sample is smooth. The light dots in both images represent chromium. Additional examination found that the particle size and distribution of chromium particles varied widely (Figure 4) and some of the particle were larger than expected.

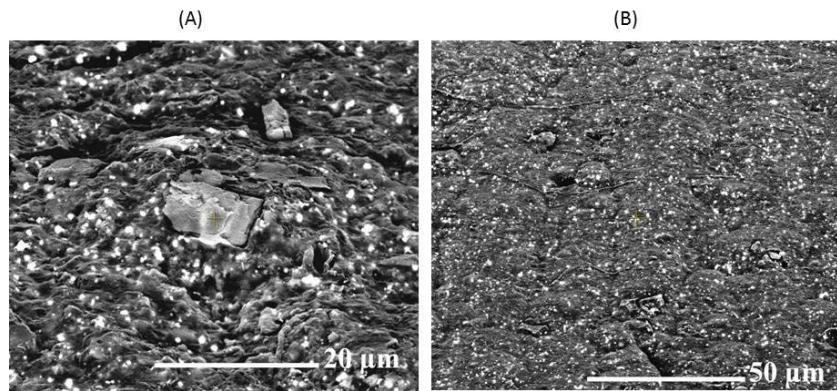


Figure 3. (A) Backscattered SEM image of the surface of the Koropon sample from the Orbiter Enterprise. (B) Backscattered SEM image of the surface of the Koropon from the control sample.

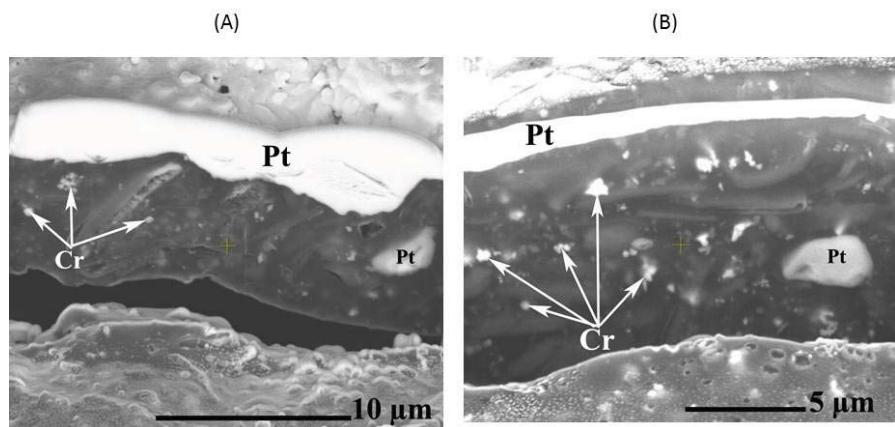


Figure 4. (A) Backscattered SEM image of the Enterprise Koropon sample showing the chromium distribution throughout the matrix in this region. (B) Backscattered SEM image of the control Koropon sample showing the chromium distribution throughout the matrix in this region.

It was concluded that the poor performance of the 30 year old Koropon primer appeared to be directly related to both a reduced level and an uneven distribution of chromium within the matrix of the film.

The CCRB used these conclusions in building rationale to either increase the inspection interval of critical areas, or as was previously mentioned strip and replace the primer. As a side note, in both commercial and military aircraft no known use of a similar primer was found anywhere

near 30 years. In most cases, primers were either inspected or replaced in the five to seven year range.

## Specific Corrosion Issues

### Rudder Speed Brake

The Rudder Speed Brake (RSB) is a structure that is deployed during landing to assist in slowing down the vehicle. The RSB is constructed from conventional aluminum ribs and spars with 2024 aluminum honeycomb skin panels. The chemical filmed honeycomb facesheet has two coating of Koropon primer and a topcoat. Part of the RSB assembly included Inconel trailing edge clips which aided in door closure. The environment of the RSB was external. They were exposed to unpurged/unconditional air during OPF processing and to the seacoast air at the Pad. Two major corrosion problems surfaced. The first was pitting corrosion in the acreage and around fasteners. This was especially problematic since the facesheet was only 0.011 thick, see Figure 5. Also galvanic corrosion was found at the faying surface between the aluminum facesheet and Inconel clips. Besides implementing basic repair procedures proactive measures introduced included washing the RSB panels upon return to the processing facility. Also, the CCRB recommended that the panels be stripped and re-coated every six missions. For the Inconel clips, a barrier layer of room temperature vulcanized rubber (RTV) was applied on the faying surfaces.

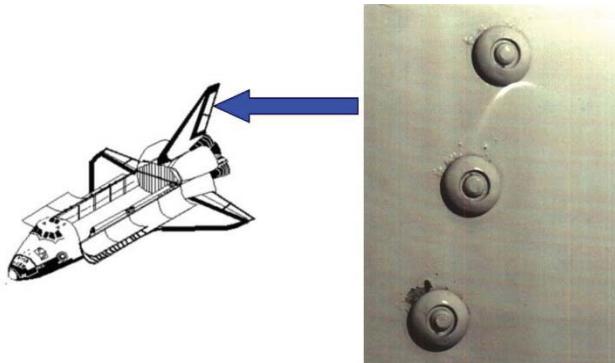


Figure 5. The Rudder Speed Brake highlighting pitting corrosion near fasteners.

### Wing Leading Edge Spar

The Wing Leading Edge (WLE) Spar was constructed of a corrugated aluminum alloy panel approximately 0.040 inches thick. The Orbiter Columbia had a slightly different design with a flat honeycomb panel structure. As shown in the left side of Figure 6 attached to the WLE spar are Inconel thermal control system blankets, Inconel attach fittings and ultimately the reinforced carbon-carbon panels. The aluminum panels were chemical film treated and coated with three coats of Koropon primer. The WLE structure is not purged.

Due to the galvanic dissimilarities between the WLE structure and the attaching hardware pitting corrosion was frequently observed, as shown in the right side of Figure 6. Like the RSB panels a barrier layer of RTV was applied to mitigate this issue. Also, a single depainting and repainting

was instituted during maintenance period. Unfortunately, the Orbiter Atlantis never experienced this and an increase inspection protocol was instituted.

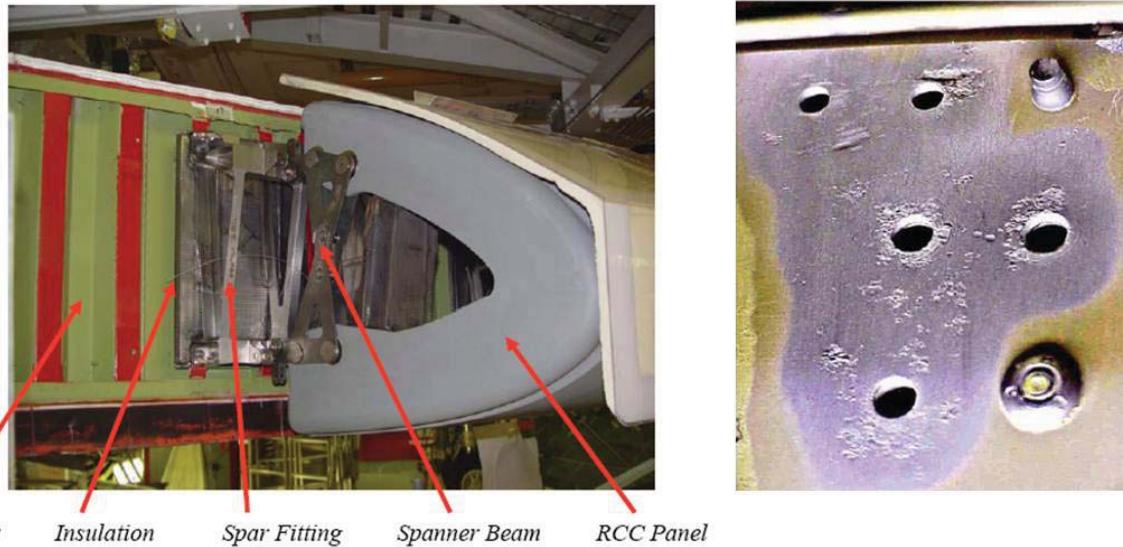


Figure 6. The basic construction of the wing leading edge and an example of pitting corrosion.

#### External Tank Doors

Each Orbiter has two External Tank (ET) on the underside of the vehicle. These doors close after the ET and Orbiter separate during ascent into Orbit. To maintain structural and thermal properties the ET doors were constructed from a beryllium alloy. Inconel support hardware was attached to each door. Over time the doors began to experience corrosion in both the open acreage and near or beneath the attach structure (Figure 7). Due to its unique metallurgical properties special care had to be taken when clean up or repair was performed. For shallow pits, the active corrosion product was removed and the pits were filled with an epoxy and recoated. For deeper pit removal or any sanding on the surface for primer removal special safety consideration were employed. For galvanically dissimilar regions an RTV barrier layer was applied.

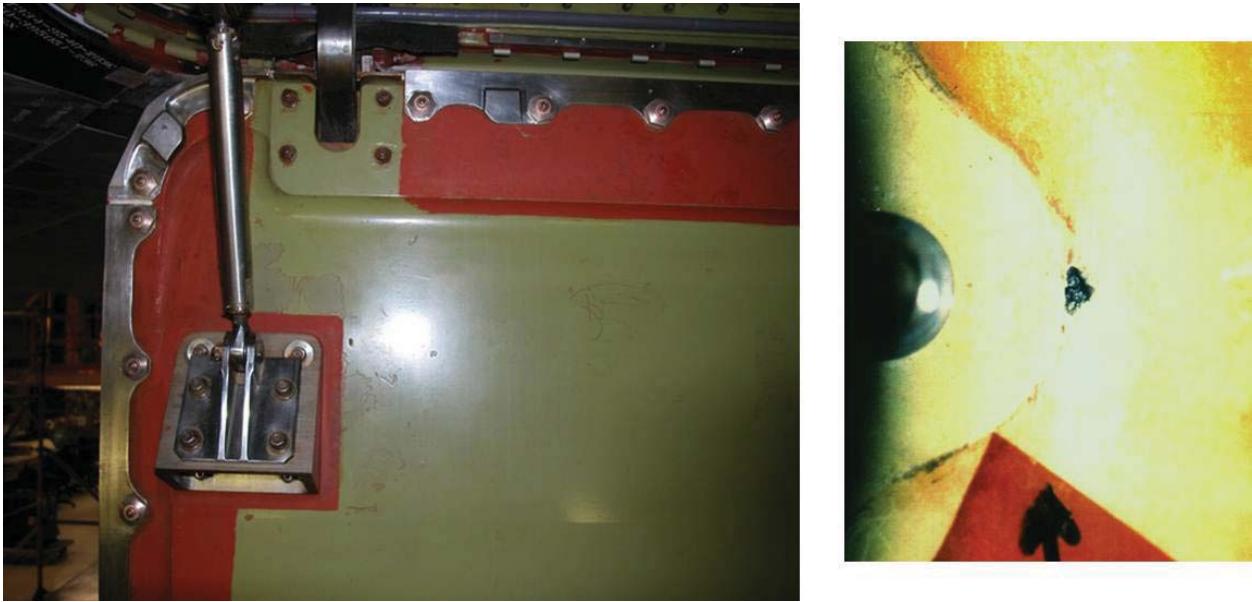


Figure 7. A close up view of the attach hardware (right) on an External Tank door after the addition of an RTV barrier layer. Typical pitting is shown on the left.

#### Nose Cap Bulkhead Corrosion

Corrosion pitting was found during routine inspections of the Nose Cap bulkheads of both Columbia and Discovery. The interface experience corrosion was one of many which were left bare to achieve an electrical bond. Electrically bonding creates a unique design challenge to the materials engineer and surfaces are designed to allow for the flow of an electrical current. To mitigate corrosion thin layers of a chemical conversion coating and a fillet seal of the joint are required. In this case the galvanic differences between titanium fillings and the aluminum bulkhead drove significant pitting. The introduction of a corrosion product not only reduces the strength of the structure but can also interfere with the conductive path this is required to maintain an electrical bond.

Figure 8 shows both the bulkhead and a close up view of the footprint for one of these electrical bonds. Pitting was found in numerous locations on the outer perimeter. For both cases the corrosion was attributed to a breach in the RTV fillet seal. Several options were suggested by the CCRB to prevent this from occurring in the future. These included the alternate use of grounding straps, the addition of an aluminum plating to the titanium faying surfaces, the addition of a conductive sealant and a change of fitting material. Unfortunately none of these changes were accepted by the program, but the lessons learned may prove to be beneficial in future designs.



Figure 8. A nose cap bulkhead after removal. The bare areas represent faying surfaces left bare for electrical bonding purposes, as seen in great detail on the right.

#### Main Landing Gear (MLG) Wheel Corrosion

The MLG Wheels are constructed of a split wheel design with 18 tie-bolts connecting the inboard and outboard halves and made from aluminum 7049/7050-T73, as shown on the left side of Figure 8. The left picture highlights corrosion pitting which was attributed to galvanic corrosion between the wheel halves and the MP35N tie-bolts. A review of the contractor cleaning procedures found also found them to be inadequate. This issue created a great concern as the pitting could act as a stress concentration point leading to fatigue cracking and failure during landing.

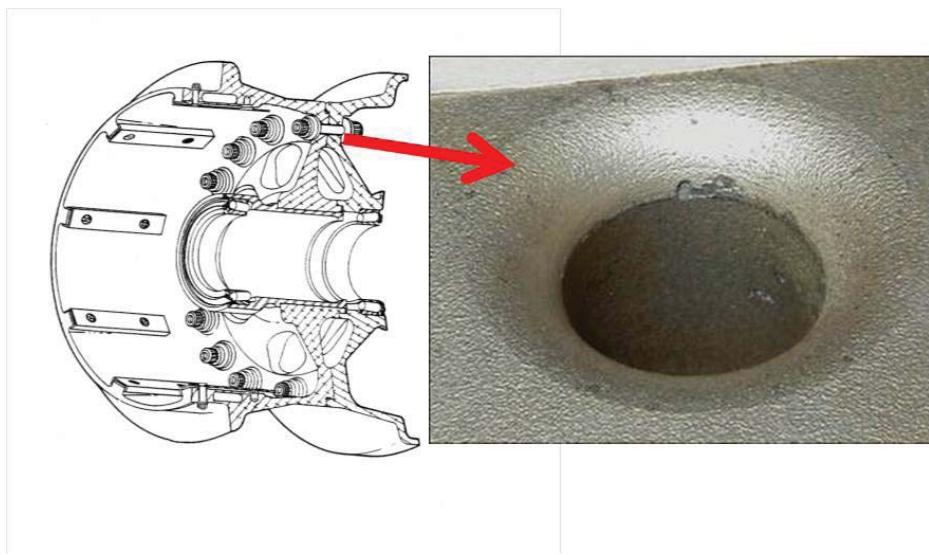


Figure 9. A schematic of the Main Landing Gear wheel designs and a close up of corrosion pitting observed adjacent to a bolt hole on the inner surface.

Fracture analysis was performed and critical flaw sizes were determined. With these flaws sizes a limited number of cycles would be allowed. To further alleviate concerns testing was performed at Wright-Patterson AFB in Dayton, OH. Landing simulation tests were performed on a wheel that had seven notches cut into the outboard wheel half by EDM to represent worst-case corrosion indications. Eddy current and dye penetration analysis after each test run found no crack growth.

Design changes were made and improved corrosion protection schemes, inspection techniques and cleaning procedures were introduced.

### **The End of the Program**

In 2006, using the tools developed during the AVA program the CCRB has developed a project plan. This plan assumes a Space Shuttle Program end date of the end of fiscal year 2010. The project plan was divided into three categories; near term (approximately one year), mid-term (approximately three years) and continuous (end of program).

The near-term project goals include creating a CCRB website, finalizing recommendations for the implementation of non-chromated primer and performing life cycle testing of CPCs. The Mid-term goals were defined as completing the development of any NDE (e.g. for corrosion under the thermal protection system) and to finalize the recommendation for the development of Laser de-painting. Finally, the continuous goals were defined as documenting lessons learned, maintaining the database, revising the Fair Wear and Tear document, updating the CPC specification, networking and benchmarking.

### **Conclusion**

After 135 missions and 30 years the Orbiter fleet was retired in 2011. Working with Orbiter project management and a world class engineering team the CCRB was successful in providing successful sustaining engineering support for approximately 20 years. Lessons learned from the Orbiter program have aided NASA and contractor engineers in the design and manufacture of new spacecraft so that exploration of space can continue. The Orbiters are proudly being displayed for all the public to see in New York City, Washington D.C., Los Angeles, and at the Kennedy Space Center in Florida.

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